SPECIAL ARTICLE

Cardiovascular Effects of Lightning Strikes

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Objectives. The purpose of this study was to investigate the effects of lightning strikes on the cardiovascular system.

Background. A lightning strike can attack its victims in one of three ways: direct hit, splash or ground strike. The cardiovascular system can be affected directly by mechanical or electrical trauma during a direct hit or can be indirectly affected through effects on the total body with extensive catecholamine release or autonomic stimulation. Reported effects include hypertension, tachycardia, nonspecific electrocardiographic (ECG) changes including prolongation of the corrected QT (QTc) interval, transient T wave inversion and myocardial necrosis with creatine kinase-MB (CK-MB) fraction release.

Methods. Nineteen victims from five separate lightning strikes were studied over a 2-month period. Each patient was evaluated by serial ECG, CK-MB determinations and echocardiography.

Results. The early (0 to 72 h) effects of lightning were demonstrated on the ECG by ST segment elevation consistent with acute current of injury, prolonged QTc interval with direct hits and nonspecific ST and T wave changes. On echocardiography, segmental or global ventricular dysfunction was seen, and pericardial effusion was also detected. During the intermediate (3- to 14-day) period, new and often marked ECG changes consistent with pericarditis or ischemia were seen. No new echocardiographic changes were detected, however, and the early abnormalities including severe left ventricular dysfunction with cardiogenic shock have reversed. The late (1 to 12 months) period revealed only one patient with long-term sequelae (recurrent pericarditis that persisted for 5 months).

Conclusions. Unless both entrance and exit sites are limited to the lower limbs, direct and splash lightning strikes cause myocardial damage as assessed by abnormal serum enzyme determinations or abnormal echocardiographic findings. Only direct hits resulted in echocardiographic abnormalities or a prolonged QTc interval. The degree of myocardial injury can be severe with left and right ventricular ejection fraction <15% and can be reversible.

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Lightning is the transfer of energy between two sources with a potential difference of up to 100,000 V. Intracloud lightning, the most common form, and cloud to cloud transfer result in no human hazard. However, cloud to ground lightning, which accounts for 20% of the estimated 8 million lightning flashes/day that occur worldwide, is a significant human hazard (1). Lightning causes more deaths than any other weather phenomenon. A recent epidemiologic description of lightning-related deaths in the United States (2) reported an average of 100 deaths/year from 1968 to 1985. These occur primarily from May to September, between 3 and 6 p.m., and affect a young group (5 to 30 years of age). Because ~30% of lightning victims die, the number of survivors is two to three times that of victims, and most survivors suffer from permanent disability (3).

The potential for dramatic survival is described in many case reports (4–6) and was reviewed eloquently by Taussig (7). Care for these patients with multisystem involvement requires a team approach and attention to the whole patient. The potential organ injuries and their treatment have been reviewed by Epperly and Stewart (1) and Craig (8). The neurological and cardiac injuries are the most serious and life-threatening.

We have had the unique opportunity to study 19 victims of five separate lightning strikes in a 2-month period. A lightning strike can affect its victims in one of three ways: direct hit, side splash or ground strike. A direct hit has an obvious entry site and causes extensive thermal injury and barotrauma. In a side splash, the lightning's current jumps through the air to the victim after directly striking an object such as a tree. The lightning may then be conducted down the tree or jump to a path of less resistance such as the persons standing under or near the tree. In a ground strike, energy after directly hitting an object is transferred through the ground and enters the body of persons in contact with the ground. The potential for and mechanism of injury to the cardiovascular system differ in each type of strike.

We observed each type of strike and report on the cardiovascular effects of each type in these patients.
Table 1. Summary of Clinical Data, Type of Lightning Strike and Extent of Cardiac Injury in 19 Patients

<table>
<thead>
<tr>
<th>No. of Strike</th>
<th>Type of Strike</th>
<th>Age (yr)</th>
<th>Gender</th>
<th>CK (U/ml)</th>
<th>CK-MB (ng/ml)</th>
<th>QTc (s)</th>
<th>ECG</th>
<th>Echo</th>
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<tr>
<td>1</td>
<td>Direct</td>
<td>31</td>
<td>M</td>
<td>1,905</td>
<td>50 (5.0)</td>
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<td>GH</td>
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<td>F</td>
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<td>M</td>
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<td>SWM</td>
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<td>5</td>
<td>Splash</td>
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<td>NSSTT</td>
<td>NL</td>
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<tr>
<td>6</td>
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<td>40</td>
<td>M</td>
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<td>7</td>
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<td>M</td>
<td>188</td>
<td>1</td>
<td>0.40</td>
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<tr>
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<td>142</td>
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<td>88</td>
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<td>0.42</td>
<td>NSSTT</td>
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<tr>
<td>17</td>
<td>Ground Strike</td>
<td>30</td>
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<td>—</td>
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<tr>
<td>18</td>
<td>Ground Strike</td>
<td>56</td>
<td>M</td>
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<td>—</td>
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<td>19</td>
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<td>50</td>
<td>M</td>
<td>156</td>
<td>1</td>
<td>0.40</td>
<td>NSSTT</td>
<td>NL</td>
</tr>
</tbody>
</table>

CK = creatine kinase; Peak CK = highest CK level during hospital stay; Peak CK-MB = highest CK-MB measured with corresponding percent of total CK measured at that time in parentheses; CK-MB = cardiac isoenzyme of CK; Echo = echocardiography; ECG = electrocardiogram segment; F = female; GH = global hypokinesia; M = male; NL = normal; NSSTT = nonspecific ST-T wave changes; QTc = corrected QT interval; ST↑ = ST segment elevation; SWM = severe wall motion abnormality.

**Methods**

**Patient data.** Nineteen victims of a lightning strike in five separate events were treated within a 2-month period: Four patients were victims of a direct hit; 3 of a side splash and 12 of a ground strike. All patients underwent triage in the emergency room of our Level 1 Trauma Center. Cardiac evaluation included physical examination, continuous cardiorespiratory monitoring, serial ECG, serum cardiac enzyme and isoenzyme determination for creatine kinase-MB fraction (CK-MB) and two-dimensional and M-mode echocardiography. Serial ECGs were obtained on admission, at 6, 12, 24, 48 and 72 h and at follow-up at 2 weeks and 3 to 6 months. An echocardiogram was obtained within 6 h of admission and repeated at 24 h, if the ultrasound study was abnormal or if myocardial injury was detected by serum enzyme determination, it was repeated at 24 to 72 h. Analysis of CK-MB (in ng/ml) was performed by fluorometric enzyme immunoassay. Myocardial injury was determined on the basis of serum enzyme evidence or echocardiographic findings. Enzyme injury was considered present if CK-MB was >6 ng/ml or CK was >1,000 IU/ml and the CK-MB/CK ratio was >35% (9). Echocardiographic injury was considered present when global or regional wall motion abnormalities were observed. Treatment of hemodynamic instability was aided by central hemodynamic monitoring with Swan-Ganz catheters. All patients were followed up until abnormal findings were resolved. Long-term follow-up data (>6 months) was available for all patients with initial cardiac injury as assessed by abnormal results on echocardiography or CK-MB determination.

**Results**

Table 1 summarizes the clinical data, type of strike and extent of cardiac injury for the 19 patients.

**Direct hit.** All four patients (Patients 1 to 4) directly hit by lightning survived the initial 24 h; one subsequently died. Patient 1 arrived in the emergency room after 20 min of asystole but, after resuscitation, returned to sinus tachycardia with a stable blood pressure. However, because of severe anoxia and multiorgan injury, he died 36 h after admission. Three of the four patients who sustained a direct hit showed evidence of myocardial injury within 4 h. Patient 4, with a right inguinal entry site and bilateral ankle exit sites, had no evidence for myocardial injury. The other three had CK-MB release, an abnormal ECG with acute current of injury, ST segment elevation (Fig. 1) and abnormal echocardiograms. By echocardiogram, Patient 1 had moderate left ventricular hypokinesia with right ventricular enlargement and hypokinesia, Patient 2 had severe left and right ventricu-
Figure 1. Patient 2. Electrocardiogram demonstrating sinus tachycardia, low voltage and ST segment elevation in precordial leads V₂ to V₅. The corrected QT (QTc) interval was reported to be prolonged (0.68 s) in a single case report (10) of one victim of a direct lightning hit. Of our 19 victims, only the 3 who sustained a direct hit and had myocardial injury had a prolonged QTc interval (range 0.47 to 0.54 s).

The two patients with cardiac injury who survived had complete resolution of the cardiac injury without residual deficit of right ventricular or left ventricular function. Patient 2 had sequelae of recurrent pericarditis that persisted for 5 months.

Patient 2 with severe myocardial dysfunction has been described elsewhere in detail (11). She was directly hit by lightning while holding an umbrella and had extensive head, chest and abdominal internal injuries. On arrival to the Level I Trauma Center, blood pressure was 80 mm Hg and heart rate was 124 beats/min. Peritoneal lavage revealed a large quantity of serosanguineous fluid. Emergency exploratory laparotomy revealed small bowel and colonic injuries. In addition, a pericardial window and drainage catheter were placed for an examination consistent with cardiac tamponade. Two hundred milliliters of serosanguineous fluid was removed with prompt improvement in hemodynamic status. The drainage catheter was left in place with subsequent drainage of 800 ml within the initial 24 h.

Cardiac function deteriorated over the first 8 h with dilated hypokinetic left and right ventricles (Fig. 2A). The thermodynamic cardiac index was 2.1 liters/min per m², and left ventricular stroke work index was 10.5 g-m/m² (normal 35 to 85 g-m/m²) with a pulmonary capillary wedge pressure of 14 mm Hg. Inotropic support with dobutamine improved function to a cardiac index of 3.8 liters/min per m² and left ventricular stroke work index to 22 g-m/m². Radionuclide ventriculography documented severe biventricular failure with a right ventricular ejection fraction of 19% and a left ventricular ejection fraction of 18%. The patient remained ventilator- and pressor-dependent for 10 days. Echocardiography showed improved left and right ventricular function, and radionuclide ventriculography on day 11 revealed a right ventricular ejection fraction of 31%.

Figure 2. Patient 2. Echocardiograms, parasternal long-axis view. A, Obtained <8 h after a direct lightning strike. The left ventricle is dilated and has a large pleural effusion seen. B, Obtained 5 months later. There is a small to moderate pericardial effusion. AO = aorta; LA = left atrium; LV = left ventricle.
ventricular ejection fraction of 44% and a left ventricular ejection fraction of 39%. Without the patient's use of pressors, heart index was 3.2 liters/min per m² and left ventricular stroke work index 23 g-m/m². Four weeks after injury and 1 week after discharge, the patient was admitted with chest pain and an abnormal ECG (Fig. 3). With no obvious intracranial process and no evidence for pericarditis, the concern was for myocardial ischemia from electrical or thermal injury to the coronary vessels. Diagnostic studies revealed a left ventricular ejection fraction by radionuclide ventriculography of 62%. Echocardiogram was normal. Right and left heart catheterization revealed normal pressures and hemodynamic variables. Left ventriculogram and coronary arteriography showed normal findings, and the patient was discharged to cardiac rehabilitation. She presented at 3 and 5 months with pleuritic chest pain, pericardial friction rub and pericardial effusion on echocardiography (Fig. 2B). At 3 months, she was treated for post-pericardiotomy syndrome with a short course (7 days) of oral steroid therapy. At 5 months the symptoms recurred and she underwent a 6-week regimen of oral steroid therapy. At 1 year, there were no recurrent episodes of pericarditis. Findings were normal on an echocardiogram and a nuclear magnetic resonance imaging study of the heart with attention to the pericardium.

**Patient 3** had severe anterior wall hypokinesia, anterior precordial acute current of injury with ST segment elevation and CK-MB release. Wall motion returned to normal by day 4 and there were no complications.

**Patient 4** sustained a direct hit to the right inguinal region with an exit site at both ankles. There was no apparent injury above the waist and no evidence of myocardial injury.

In all patients with a direct hit, ventricular ectopic activity was limited to isolated premature ventricular contractions and couplets. No ventricular tachycardia, specifically no torsade de pointes, was detected. Empiric antiarrhythmic therapy was not used in any patient.

**Discussion**

The cardiovascular effects of lightning strikes have been published either as single case reports or as reports of a single-group strike. The cardiovascular effects of this ultimate cardioversion depend on the type of strike. Lightning is high voltage, direct current and of a very brief duration. Its immediate effect can be asystole, ventricular fibrillation or direct central nervous system injury to the respiratory center. Resuscitation should be attempted on all patients who appear lifeless because extraordinary recoveries have been reported. The mechanism postulated by Epperly and Stewart (1) is that all cellular metabolism simultaneously stops at

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**Figure 3.** Patient 2. Electrocardiogram with abnormally deep, symmetrically inverted T waves.
the time of the initial strike, causing the harmful effects of anoxia to be delayed.

**Cardiovascular effects of a direct hit.** Our study shows important differences in the effects on the cardiovascular system depending on the type of strike. A direct strike is the result of a cloud to ground strike. In some direct strikes this discharge occurs at a point above the ground when an electrical potential arises from the earth to meet the advancing lightning bolt. In other direct strikes, lightning strikes objects that are the best available conductors in the area. Metal objects such as umbrellas and golf clubs serve as targets. The strike results in the transfer of a portion of the extremely high voltage and variable direct current. Deep burns can occur and superficial burns are common. The current is conducted through the body at different rates and ratios owing to the varied resistance of tissues. Nerve and blood vessels are good conductors with low resistance whereas fat and bone have high resistance (12).

A direct hit can cause injury by a second mechanism that probably accounts for most of the organ destruction seen with this type of injury. The air that is superheated by the lightning discharge to temperatures >10,000°F rapidly expands in a cylindrical column. The column is the result of decay of the shock wave to a sound wave. The dissipated energy results in mechanical trauma to any organ in its path. A strike whose path crosses the chest can result in localized myocardial contusion (as described by Hanson and McIlwraith [4] on autopsy of victim) or in severe global dysfunction that behaves like stunned myocardium.

Our study shows that a direct strike results in a high incidence of cardiac injury that can be manifested early as life-threatening pericardial effusion or severe global cardiac...
dysfunction. The outcome in Patient 2 supports prior findings (4) that ventricular dysfunction is reversible even when severe. QTc prolongation appears to be limited to victims of a direct hit. The cause of this cannot be established. Palmer (10) proposed that the QTc prolongation was due to electrical injury of the heart similar to that reported after direct current cardioversion or pacing. In three of our patients and in one patient of Palmer's study, the QTc corrected was not likely caused by a preceding condition. Because of the high incidence of cardiac involvement, it is recommended that all directly hit patients be continuously monitored with close attention to the early development of potentially life-threatening pericardial effusion or cardiac dysfunction. Maximal ventilatory and hemodynamic supportive care should be given as the potential for full recovery is excellent. Late sequelae were seen in any type of strike; it occurred in 75% of victims of a direct hit, 66% of victims of a splash and 12% of victims of a ground strike. Cardiac dysfunction including severe biventricular failure is reversible within 2 weeks. A direct hit can result in early significant life-threatening pericardial effusions.

Abnormalities of the ECG also vary with the type of strike. Current of injury, ST elevation and QTc interval prolongation occurred in victims of a direct hit. ECG changes after splash and ground strikes were limited to nonspecific ST-T wave changes. Marked T wave inversion with ST depression can be seen without associated central nervous system or coronary artery abnormalities and appears secondary to the lightning strike. Late sequelae were limited to a single case of recurrent pericarditis.

Cardiovascular effects of a side splash. More common than a direct hit is a splash. Lightning directly strikes an object such as a tree. The current can now be conducted down the tree or jump to a path of less resistance such as a victim standing under or near the tree. This jump often results in a characteristic superficial burn (Fig. 4) giving its name “splash.” In this type of strike, mechanical trauma from the cylindrical shock wave is not likely unless the distance between the direct hit and the victim is short. Wet clothing or wet skin results in a low resistance pathway over the body exterior in a phenomenon known as flashover. This results in less internal injury. Our patients who sustained splash injury had myocardial injuries manifested as CK-MB release, but they had normal echocardiograms and no ECG evidence of current of injury. The ECG abnormalities were limited to nonspecific ST-T wave changes and no late sequelae were detected.

Cardiovascular effects of a ground strike. The third mechanism is the result of a ground strike. Although no direct hit or splash is involved, as the current spreads through the ground, it may enter a victim whose body, in contact with the ground, provides a path of less resistance. Most common, this is from leg to leg but can be any entrance or exit site that provides a pathway.

Our patients who were victims of a ground strike had only nonspecific ST-T wave changes on ECG and had no echocardiographic abnormalities. One patient who was lying on the ground did have CK-MB release. No sequelae were seen in follow-up.

Conclusions. The type of lightning strike affects the type of injury to the cardiovascular system. Abnormal findings on echocardiograms were seen only in victims of a direct hit. Myocardial injury as assessed by CK-MB release can be seen in any type of strike; it occurred in 75% of victims of a direct hit, 66% of victims of a splash and 12% of victims of a ground strike. Cardiac dysfunction including severe biventricular failure is reversible within 2 weeks. A direct hit can result in early significant life-threatening pericardial effusions.

References